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Ultrasonic measurements of undamaged concrete layer thickness in a deteriorated concrete structure

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ABSTRACT

Ultrasonic wave propagation in deteriorated concrete structures was studied numerically and experimentally. Ultrasonic single-side access immersion pulse-echo and diffuse field measurements were performed in deteriorated concrete structures at 0.5 MHz center frequency. Numerically and experimentally it is shown that the undamaged layer thickness in a deteriorated concrete structure is measurable using pulse-echo measurements when the deterioration depth is larger than the wavelength. The signal overlapping, which occurs in the thin deteriorated layers, can be overcome using diffuse field measurements or a pattern matching technique. The ultrasonic experimental data were shown to be in good agreement with the widely used phenolphthalein test for concrete degradation.

1. Introduction

When concrete pipelines are buried in an aggressive soil, the physico-chemical aggressivity of the environment causes deterioration in the concrete; resulting in a decrease in strength of the concrete over time. In the early stages of deterioration a thin deteriorated layer is induced in the concrete structure. In a general case the physico-chemical damage may occur from both sides of the structure: from both internal and external surfaces [1]. Therefore, a measurement technique, used for the inspection of deteriorated concrete structures, must work reliably at different inspection conditions: from both the undamaged and the deteriorated side of the structure. Various inspection techniques such as visual, electromagnetics, acoustics and ultrasonics are used for concrete structure testing [2–4]. Acoustic methods are especially attractive for inspection of water mains due to the possibility of immersion ultrasonic measurements from the inside. Hence, the measurements are contactless and suitable for automatic robotic scanning.

Ultrasonic measurements have been widely used for the characterization of concrete structures for a long time, for example, see the reported work [5] which presents the characterization of concrete structures by means of the analysis of the speed of ultrasonic pulse propagation. The ultrasonic frequency range used for concrete characterization, depends on the following conditions: (a) concrete structure or/and concrete mixture (including its aggregate size), (b) structural thickness, and (c) measurement method. Therefore, the frequency of the ultrasonic wave must be selected according to the measurement conditions very carefully. It is necessary to use high frequency ultrasonics in the frequency range of 0.5–1 MHz to detect the early stages of deterioration in concrete and to measure thin deteriorated layers using conventional ultrasonics such as pulse-echo technique [6]. However, to perform measurements at high frequencies, for example at 1 MHz center frequency, is complicated when a deteriorated layer is present in the concrete structure. The difficulties arise due to the high acoustic losses which exist in the deteriorated concrete layer and these losses are caused by high scattering. In the reported work [6] the through-transmission measurement mode was used, and this measurement mode enabled the signal to noise ratio to be improved. However, through-transmission measurements are not suitable for inspection of buried pipes or other structures when only a single-side access to the structure is possible.

As an alternative to bulk wave ultrasonic techniques, different acoustic measurements have been used for the characterization of concrete deterioration. For example, different guided wave techniques have been used such as the surface wave technique which is limited to the measurement of the accessible surface of the structure [3,7,8] (therefore it is not analyzed in detail in this study) and the guided ultrasonic technique [2,9]. The latter technique is attractive for field inspections, because the guided waves may propagate over a long range (up to a few hundred meters). However, with this technique the detection of local low level deterioration zones is questionable. Moreover, with the current state of the technique it is only possible to determine an average status of

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the concrete structure within the inspection region. However, low frequency guided waves can be used over a short range [10]. But in this case to generate a single guided wave mode becomes difficult, therefore it is complicated to utilize this kind of technique for field measurements when only single-side access to a structure is allowed [10]. A low density of the deteriorated concrete also causes problems for the use of guided ultrasonics for inspection of the buried concrete pipes. The density of the deteriorated concrete may become close to the density of the soil, therefore Cremer's principle is not valid anymore [11]. Practically this means that the propagation of the guided waves will depend on the acoustic loading. For example, the properties of the soil will affect the guided wave propagation in the buried pipe case.

Recently developed acoustic techniques, used for evaluation of concrete properties, have investigated various nonlinear ultrasonic techniques such as harmonic generation [12], wave mixing [13] and diffuse field techniques [14–20]. The use of nonlinear ultrasonics for concrete inspection is attractive due to the high nonlinearity of the concrete and very high sensitivity of the nonlinear ultrasonics to various types of damage. Usually the nonlinearity of the concrete is one order higher than in metals [21]. However, it is difficult to implement nonlinear ultrasonics measurements based on the harmonic generation due to various parasitic nonlinearities which distort the received harmonics. Wave mixing techniques can be used to overcome these distortions, but it requires a more sophisticated and complex acoustic configuration for the experiments [22,23].

Diffuse field measurements also demonstrate a very high sensitivity to material changes. The simplicity of a practical realization of a diffuse field acoustic measurement makes this technique more attractive for practical measurements than the application of nonlinear ultrasonics. First of all, the diffuse field technique does not require the ultrasonic transducers to be oriented at a specific angle, i.e. the inclination of the transducers is perpendicular to object's surface. Secondly, it is easy to combine the diffuse field measurements with pulse-echo measurements, i.e. the same acoustic measurement configuration can be used during both experiments.

Single-side access immersion ultrasonic measurements of the undamaged concrete layer thickness in deteriorated concrete structures is the key issue of this study. Pulse-echo and diffuse field measurements are performed at a center frequency of 0.5 MHz on concrete specimens. The pulse-echo measurement results from the test specimens are verified by the standard phenolphthalein tests [24] and pattern matching technique [25].

This paper is structured as follows. The opening two sections describe the preparation procedure which was used for the production of the concrete specimens with different deterioration levels and presents the two ultrasonic measurement methods, used for the evaluation of the concrete. Then initial non-acoustic and acoustic characterizations of undamaged and deteriorated concrete specimens are presented. Next to the measured material properties, a multi-layered wave propagation model is utilized for prediction of ultrasonic signals reflected from the deteriorated concrete specimens at different deterioration conditions is presented. Subsequently the experimental results for pulse-echo and diffuse field measurements are presented. Finally, the phenolphthalein test results of the concrete deterioration are presented and compared with the acoustic results and numerical predictions.

2. Specimens

9 specimens were prepared from components listed in Table 1. The specimens had approximate dimensions 30 mm × 100 mm × 290 mm. An HCl acid solution of 20% was used to induce and accelerate a chemical deterioration in the concrete specimens [26] (for the description of the chemical reactions occurring, see [27]). In the reported work [28] an analysis of concrete mechanical properties when the concrete is deteriorated using HCl solution is presented.

Table 1
Concrete mixture components by ratio of mass fraction. Fine quartz sand is from the current Dutch stock.

	Cement	Quartz sand	Water	Plasticizer
Ratio	1	0.5685	0.2041	0.0026

Table 2
Concrete treatment time by the 20% HCl acid solution. The reference specimen is not listed in the table.

Time, h	Single-sided deteriorated	168	336	504	672	1008
	Double-sided deteriorated for each side		336	504	672	

The following procedure was used for the concrete treatment by the acid solution. A single-side of a raw concrete specimen was kept in a box with the acid solution. The box contained 0.5 l of the acid solution. A partial immersion of the specimens was achieved in this way, keeping the un-immersed side in air. The specimen submersion depth was 14–15 mm. The specimens were kept for at least one week in the acid solution. After this, the specimens were washed with fresh water and some specimens were immersed in a fresh acid solution for another week. In this way, concrete specimens with different deterioration levels were produced. The concrete treatment time by the acid solution is listed in Table 2.

Single-sided and double-sided deteriorated concrete specimens were prepared (see Table 2) for investigation of different measurement conditions. The double-sided deterioration specimens were kept in the acid solution identical time periods from both sides. Each side of the specimen was immersed into the acid solution separately. During the treatment of the second surface of the concrete specimen, it was found that the first deteriorated surface became wet in air. This never happened for the single-sided deteriorated specimens. The wetting of the un-immersed surfaces was attributed to the acid propagation via micro-capillaries which were formed by the acid treatment of the first surface.

3. Ultrasonic measurement methods

Two different ultrasonic measurement methods are used in the measurement of the undamaged layer thickness in the concrete specimens: (a) pulse-echo and (b) diffuse field technique. Both measurement configurations are presented in Fig. 1. Due to the advantages of immersion based ultrasonic measurement techniques, the experiments are performed in a water tank employing an ultrasonic scanner. B-scanning measurements were performed at the center part of the specimens (see Fig. 1, dark gray area). A step size of 1 mm is used in the scanning direction.

The pulse-echo measurement configuration, which involves a single ultrasonic transducer operating in transmission and reception modes, (Fig. 1(a)) is attractive for industrial measurements due to its simplicity in practical implementation and signal processing. However, this measurement configuration has a limited discriminating capacity for the estimation of the structural state of the concrete. The limitations of the pulse-echo measurement configuration are presented and discussed in section *V*.